# Boundary Conditions, Data Assimilation, and Predictability in Coastal Ocean Models

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## LONG-TERM GOALS

The long-terms goals of this research are to improve our ability to understand and predict environmental conditions in the coastal ocean.

## OBJECTIVES

The specific objectives of this research are to determine the impact on coastal ocean circulation models of boundary conditions from data-assimilating large-scale models, and to address related issues of uncertainty and predictability in coastal ocean models.

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE **2009** | 2. REPORT TYPE | 3. DATES COVERED **00-00-2009 to 00-00-2009** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE **Boundary Conditions, Data Assimilation, and Predictability in Coastal Ocean Models** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Ocean Sciences Branch, Code 7331,Stennis Space Center,MS,39529-5004** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT **unclassified** | b. ABSTRACT **unclassified** | c. THIS PAGE **unclassified** | **Same as Report (SAR)** | **5** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

## APPROACH

This research addresses the direct impact on coastal models of boundary conditions from GODAE models. The domain of the nested coastal model is the 'coastal transition zone' (CTZ), which includes the continental shelf and slope, and the adjacent ocean interior. The CTZ extends offshore about 200 km in this region, and is characterized by energetic wind- and buoyancy-driven flow over the shelf, accompanied by complex, lower-frequency eddy, jet and filament dominated flow over the slope and in the ocean interior, which is unlikely to be properly resolved by basin scale models. Validation of the simulated coastal ocean circulation is provided by existing elements of the Oregon coastal ocean observing system. The closely related issues of uncertainty and predictability in coastal ocean models are being addressed using a variety of empirical and theoretical methods to study disturbance growth mechanisms and to develop uncertainty budgets for these models.

In addition to PIs Samelson, Allen, Egbert, Shulman (who has replaced the recently retired John Kindle), and Snyder, other senior personnel are A. Kurapov and R. Miller, both at Oregon State University. Dr. Scott Springer has been a full-time research associate pursuing physical circulation modeling, and postdoctoral investigator Dr. Sangil Kim has worked on studies of predictability and uncertainty, and assessment of boundary condition effects.

## WORK COMPLETED

The work plan primarily involves the implementation, evaluation, and analysis of nested primitive-equation CTZ-domain models. Since the GODAE Pacific HYCOM model was not yet functioning with full data assimilation capability, it was decided to proceed with nesting the CTZ-domain model in the data-assimilating NRL regional NCOM-CCS (Navy Coastal Ocean Model-California Current System) model.

Simulations and detailed comparisons with observations have been carried out during for the period 1 May through 1 November 2001, and described in a publication (Springer et al., 2009). A continuation study that focuses on the downwelling season of winter 2002-2003 has been completed and presented at a national meeting (Springer et al., 2008). Additional simulations conducted by part-time research associate Dr. Scott Durski have addressed the development of bottom-trapped symmetric and surface-intensified baroclinic instabilities under wintertime downwelling conditions.

To address the predictability of wind-driven flow over the shelf, ensembles of simulations of wind-forced coastal ocean circulation in a periodic alongshore-channel CTZ domain have been analyzed, and the results have been described in a publication (Kim et al., 2009a). Building upon these results, similar methods have been used to construct an approximate uncertainty budget for a coastal ocean model (Kim et al., 2009b).

## RESULTS

For the May through November 2001 OCTZ simulations, the nested model was found to provide a useful representation of flows both over the shelf and farther offshore that was quantitatively improved relative to previous regional models (Springer et al., 2009).

The downwelling season simulation covers the period from October 1, 2002 to May 1, 2003. As for the summer 2001 simulation, the nested model obtains initial conditions and boundary conditions from the

NRL NCOM-CCS model and is forced by surface fluxes from reanalyses and by observed coastal river flows. Initially, an upwelling circulation established by predominantly southward winds during the previous summer is in place. Vigorous cyclonic storms in December deepen and freshen the mixed layer in offshore regions, and establish a coastal downwelling circulation, characterized by a density front over the midshelf (~50 m depth) and northward surface jet. Riverine freshwater input is held close to the shore by onshore Ekman transport. When the wind reverses to upwelling-favorable, this freshwater feature is released and spreads over the entire shelf. Comparison with high-resolution hydrography shows that the model simulates this event in a realistic way. During the latter half of the winter, the wind stress alternates between strongly downwelling-favorable and weakly upwelling-favorable. Comparison with an across-shelf array of current meter moorings shows that the model realistically represents the corresponding reversals of the depth-averaged alongshore currents, although the simulated currents are somewhat weak during downwelling events. The northward currents are stronger than can be explained by local winds and reflect the influence of coastal-trapped waves propagating from the south, where upwelling favorable winds are established earlier and more strongly. Although the model simulation represents the depth of the mixed layer in spring realistically, deeper (100-200 m) stratification is too weak because the model does not include the permanent halocline that is a ubiquitous feature of the north Pacific Ocean. This flaw is inherited from the larger scale California Current model that is used to provide initial and boundary conditions for the nested model. The remote influence of coastal trapped waves on alongshore currents and coastal sea level in these wintertime simulations demonstrates the importance of accurate open boundary conditions adjacent to the coast along the southern open boundary (Figure 1). Similar results were found previously in this project for summertime flows (Springer et al., 2009).

The development of instabilities under downwelling conditions have been studied with numerical solutions in an alongshore-uniform domain, with steady downwelling wind forcing and initial conditions consisting of a state of rest with stratification from Oregon coastal ocean CTD data from October 2002 (Figure 1). Initially, alongshore-uniform symmetric instabilities develop along the bottom slope, which give way to baroclinic instabilities as the flow evolves. Symmetric instabilities interact with and persist offshore of the baroclinic instability structures. The alongshore scale of the baroclinic instability structures increases between the time of their onset (around day 13) through Day 17-18. After this time, the flow becomes more complex, and associating a particular scale to the disturbance structure becomes more difficult. This interactive development of symmetric and baroclinic instabilities for idealized wintertime downwelling conditions differs substantially from the characteristic coastal jet evolution found for summertime upwelling forcing.

In the predictability studies, which used ensembles of 50-day primitive-equation ocean model simulations with realistic topography, simplified lateral boundary conditions, and forcing from both idealized and observed wind time-series representative of the summer upwelling season, large ensemble and single-simulation variances were found downstream of major topographic features on the shelf. The simulated predictability experimentssuggested that that important elements of the coastal circulation should be accessible to predictive, dynamical forecasts on the nominal 7-day predictability timescale of atmospheric forcing. A new variant of relative entropy, the forecast relative entropy, was introduced to quantify the predictive information content in the forecast ensemble, relative to the initial ensemble. More details on these simulations and results are provided by Kim et al. (2009a).

These results on predictability have been extended to obtain ensemble-based estimates of components of an uncertainty budget for the coastal ocean model (Kim et al., 2009b). In these estimates, a distinction is made between the shelf regime, inshore of the 200-m isobath, and a slope- interior regime,

between the 200-m isobath and a fixed longitude (126 $^{o}$W) that is roughly 150 km offshore. The focus is on three components of the budget, each of which behave differently in these two different geographical and dynamical regimes. The first of the three budget components is an estimate of the uncertainty in the ocean state given only a known history of wind stress forcing, with errors in the wind forcing estimated from differences between operational analyses. This component is of particular interest over the continental shelf, where the response to wind forcing is sufficiently strong and deterministic that significant skill in estimating shelf circulation can be achieved with knowledge only of the wind forcing, and no ocean data, for wind fields with errors estimated from the differences between operational analyses. The second involves initial condition error and its influence on uncertainty, including both error growth with time from well-known initial conditions and error decay with time from poorly known initial conditions but with well-known wind forcing. Time scales for the initial condition error growth and decay are roughly 5 days for the shelf regime and 12 days for the slope-interior regime. The third component is that of boundary condition error and its influence on the interior solutions, including the dependence of that influence on the specific location along the boundary of the boundary condition error. Boundary condition errors with amplitude comparable to the root-mean-square variability at the boundary lead eventually to errors equal to the root-mean-square variability in the slope-interior regime, and somewhat smaller errors in the shelf regime (Figure 2). For both regimes, errors along the shelf-regime portion of the northern and southern boundaries appear to generate errors within the respective domain interiors more efficiently than errors along the slope-interior portion of the boundary.

## RELATED PROJECTS

The research in this NOPP project has been closely coordinated with work in the OSU component of the GLOBEC/NEP project 'US-GLOBEC/NEP Phase IIIa – CCS: Effects of Meso- and Basin-Scale Variability on Zooplankton Populations in the CCS Using Data-Assimilative, Physical/Ecosystem Models' and in the OSU ONR project 'Data Assimilation in Shelf Circulation Models.'

## REFERENCES

Kim, S., C. Snyder, and R. M. Samelson. 2009b. Toward an uncertainty budget for a coastal ocean model. Manuscript in preparation.

Springer, S. R., J. S. Allen, R. M. Samelson, A.L. Kurapov, G.D. Egbert, R.N. Miller, S. de Rada (2008), Simulations and Observations of Circulation in the Oregon Coastal Transition Zone during the 2002-2003 Downwelling Season, Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract OS53D-1344

## PUBLICATIONS

Kim, S., R. M. Samelson, and C. Snyder. 2009a. Ensemble-based estimates of the predictability of wind-driven coastal ocean flow over topography. Monthly Weather Review, in press.

Springer, S. R., R.M. Samelson, J. S. Allen, G. D. Egbert, A. L. Kurapov, R. N. Miller and J. C. Kindle, 2009. A Nested Grid Model of the Oregon Coastal Transition Zone: Simulations and Comparisons with Observations During the 2001 Upwelling Season. Journal of Geophysical Research - Oceans, 114, C02010, doi:10.1029/2008JC004863.

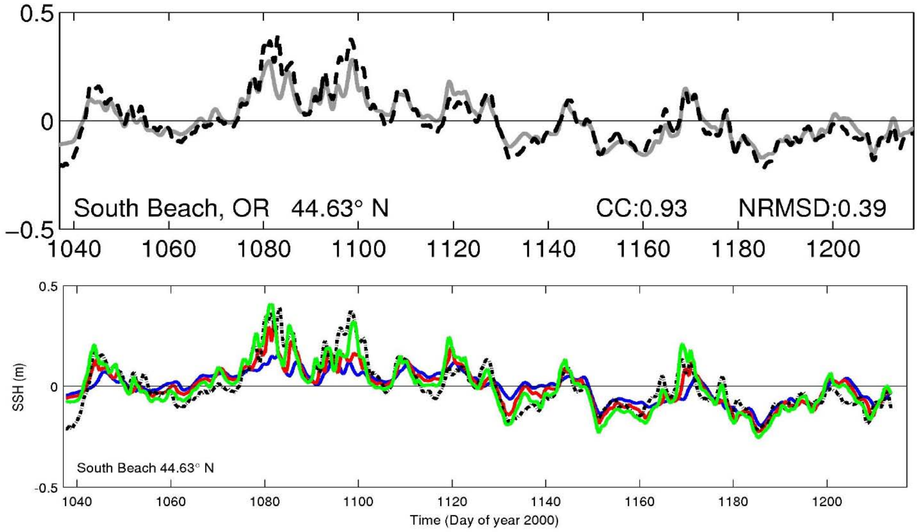


***Figure 1: Modeled and observed sea level (m) at Newport (South Beach), OR, vs. day (1 October 2002 to 1 May 2003). Upper panel: Observations (thick dashed line) and OCTZ model (gray solid). Lower panel: Observations (dashed-dotted line) and coastal-trapped wave model forced by winds south of the OCTZ domain (blue), south of 42 $^{o}$N only (red), and south of Newport (green). The portion of the signal contributed by winds south of the OCTZ domain (lower panel, blue) is a major component of the signal and enters the OCTZ numerical model (upper panel, gray) only through the southern boundary condition provided from the large-scale outer model.***

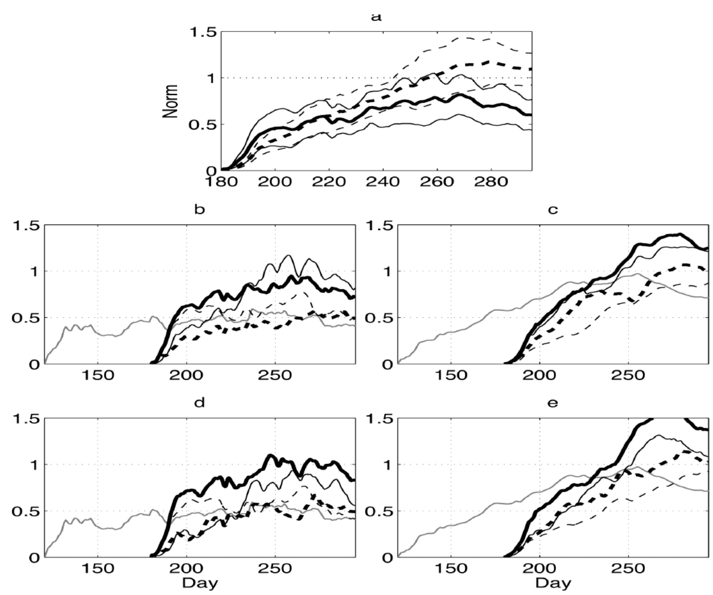


***Figure 2: Normalized ensemble variance vs. time (days) with perturbed boundary conditions. (a) Mean (thick lines) and the mean+/-standard deviation (thin) for three simulations with independent realizations of all boundary perturbations, for the onshore (solid) and offshore (dashed) regions. (b,d) Onshore (coastline to 200-m isobath) region vs. time for perturbations on all open boundaries (thick solid line), the western slope-interior boundary only (thin solid), the southern boundary over the shelf only (thick dashed), and the northern boundary over the shelf only (thin dashed). (c,e) As in (b,d) but for the offshore (200-m isobath to 126 $^{o}$W) region. In (b-e), the ensemble-mean variances from (a) are also shown (gray solid from Day 120).***